Review

The discovery of CP violation in B-meson decays

By Fumihiko TAKASAKI[*1,†]

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Abstract: We present the KEK B-factory project, which discovered CP violation in B-meson decays and proved that the Kobayashi-Maskawa theory correctly explains CP violation in meson decays.

Keyword: B-factory

1. Introduction

In 2001, CP violation of B-meson decay was discovered by two experiments: the Belle experiment[1] at KEK and the Babar experiment[2] at SLAC. It is the first discovery of the CP violation in meson decays other than in neutral K-meson decays[3] and it proved that the CP violation in meson decays can be explained by the theory formulated by Makoto Kobayashi and Toshihide Maskawa in 1973.[4] In this article, we present how the B-factory project started at KEK and how the discovery of CP violation in B-meson decay was made. More rigorous description on this subject can be found in reference 1 and references there in. As for the description of the KEK B-factory project in the start-up days, there is an article by H. Sugawara[5] and an article by Y. Kimura.[6] The details of the KEK B-Factory Project can be also found in the references 37 and 47. This manuscript has many overlaps of description with these papers.

M. Kobayashi and T. Maskawa studied the phenomenon of the CP violation in the neutral K-meson, K^0, within the framework of $SU(2) \times U(1)$ theory of Glashow-Weinberg-Salam[7] and found that if there exist at least six quarks grouped in three doublets, CP violation in Kaon-decays can be explained. When their paper was published, there were three quarks known to exist: up-, down- and strange-quarks. The study of Kobayashi and Maskawa was substantiated by the discoveries of the

charm quark in 1974[8] and the bottom quark in 1977.[9] There remained one missing member of quarks, the top quark.[10] New accelerators were built aiming to search for the top quark as one of their major research goals. They include following electron-positron colliders: PEP[11] in the U.S.A., PETRA[12] in Germany, TRISTAN[13] in Japan, SLC[14] in the U.S.A. and LEP[15] built on the border of Switzerland and France. They were built with increasingly higher center of mass energies. Unfortunately, the mass of the top quark was beyond the energy reach of all of them. One half of the maximum center of mass energy of LEP was about 100 GeV, about 20 times larger than the mass of the bottom quark, a partner of the top quark in the same doublet, but LEP could not find the top quark.

Besides electron-positron colliders, hadron-hadron colliders[16] were also built, for example the Intersecting Storage Rings which were built at CERN and operated from 1971 to 1984 with a center-of-mass energy of 60 GeV, and the proton-anti-proton collider which was also built at CERN and operated from 1981 to 1984 with a center-of-mass energy of up to 630 GeV. The top quark was finally discovered in 1995 at the proton-anti-proton collider TEVATRON,[17] at FNAL in the U.S.A., whose center of mass energy reached 2 TeV. The mass of the top quark was about 175 GeV.[10] All of three doublets of quarks were found as postulated by M. Kobayashi and T. Maskawa.

Along with the discovery of new quarks, the tau lepton was discovered in 1977,[18] and leptons (electron, muon and tau) are also considered to be grouped in three lepton doublet with their partner neutrinos[19] in a similar manner as quarks. Since the Weak bosons,[20] W and Z, were found as predicted

*1   KEK, High Energy Accelerator Research Organization, Tsukuba, Japan.

†   Correspondence should be addressed: F. Takasaki, KEK, High Energy Accelerator Research Organization, Oho 1-1, Tsukuba, Ibaraki 305-0801, Japan (e-mail: fumihiko.takasaki@kek.jp).
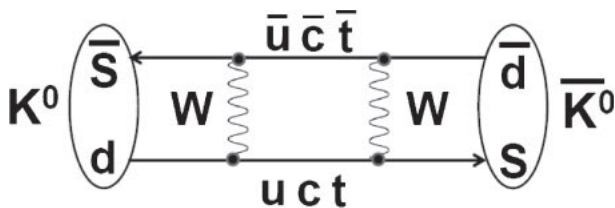
Fig. 1. K^0-$\bar{K}^0$ mixing diagram.

by the theory of Glashow-Weinberg-Salam,[7] most particles in the Standard Model have been found.

2. K-meson mixing and CP violation

The neutral K meson consists of a d-quark and an anti-s-quark, $\bar{s}$. It was known that the neutral K meson, K^0, mixes with its anti-particle, $\bar{K}^0$. One of the possible diagrams which make this phenomenon to happen is shown in Fig. 1.

In this diagram, the anti-s-quark, $\bar{s}$, in the K meson changes to an anti-up-type quark (such as a $\bar{u}$, $\bar{c}$ and $\bar{t}$ quark) by emitting a W^+ boson. At the same time, the d-quark in the same K meson changes to an up-type quark by absorbing the emitted W^+ boson. Then generated anti-up type quark changes to an anti-d-quark, $\bar{d}$, by emitting a W^- boson, which is absorbed by an up-type quark in the K^0 meson and change it to a d-quark. Through this process, a K^0 meson can change to its anti-meson, $\bar{K}^0$. Because of the mixing, the physical particle states (mass eigenstates) are mixtures of K^0 and $\bar{K}^0$ mesons, according to quantum theory. They are the K_S with CP eigenvalue "+" and the K_L with CP eigen-value "−".

It was believed that the CP eigen-value conserves in any processes of particle interactions. Therefore, a CP odd state, K_L, was believed not to decay into two π-mesons, a CP even state.

In 1964, it was found that K_L decays to two π-mesons by J. Cronin and V. Fitch and their collaborators.[3] This marks the discovery of violation of CP symmetry in neutral K-meson decay processes. The violation of CP symmetry is also called "CP violation".

As mentioned before, M. Kobayashi and T. Maskawa studied the CP violation phenomenon within the framework of the $SU(2) \times U(1)$ theory of weak interaction. They concluded that if there exist at least three doublets of quarks, it is possible to accommodate one non-erasable complex phase in the transition amplitudes between up-type quarks and down-type quarks in the quark doublets, and this complex phase induces the CP violation in K-meson decays.

Since the discovery of the CP violation in K-meson decay, many attempts were made to look for CP violation processes other than neutral K-meson decays. However, no CP violating process had been found except for neutral K-meson decays.

3. B-meson, B-$\bar{B}$ mixing and CP violation

After the discovery of the Upsilon resonances at FNAL[9] in 1977, properties of B-meson have been studied extensively by the electron-positron colliders, PEP,[11] PETRA,[12] DORIS-II[21] and the CESR,[22] especially at DORIS-II and CESR.

The B^0-meson was discovered in 1983 in the decay of the Upsilon (4S) resonance.[23] The B^0 meson is a bound state of an anti-b-quark, $\bar{b}$, and a d-quark, d. Its anti-particle, $\bar{B}^0$, is a bound state of a b-quark, b, and an anti-d quark, $\bar{d}$. The Upsilon (4S) resonance turned out to be an excellent object for the study B-mesons because it decays exclusively to two B-mesons. Its mass, 10,580 MeV, is just above the threshold of production of two B-mesons. (The mass of the B^0-meson is measured to be 5,279.5 MeV.) The Upsilon (4S) resonance decays to a B-meson and anti-B-meson pair without accompanying any hadrons or energetic photons. The decay branching ratio to a B-meson pair is larger than 96%.[24] The lifetime of the B-meson was found to be an unexpectedly long, ∼1.6 psec,[25),26] considering its heavy mass. B-mesons are produced with very small momentum, 328 MeV/c, in the rest frame of the Upsilon (4S) resonance. The mean decay length of produced B-mesons in the rest frame of the Upsilon is about 28 μm. The cross section to produce the Upsilon (4S) resonance by the electron-positron annihilation was measured in 1980.[21]

It should be mentioned that studies of B-mesons at symmetric energy electron-positron colliders with high luminosity[27] and also those at hadron colliders[28] were widely discussed.

It was A.I. Sanda and his collaborators[29] who noticed in 1980 the possibility of B-meson mixing with its anti-particle and also the possibility of observing CP violation in B-meson decay within the frame work of the Kobayashi-Maskawa theory well before the discovery of B-meson mixing.[30]

It was in 1987 when a large mixing of B^0-meson with its anti-particle, the anti-B^0-meson ($\bar{B}^0$), was discovered by the ARGUS collaboration[30] at DORIS. The B-meson mixing can be naturally understood if one thinks of a diagram similar to the one shown in Fig. 1 in which the s-quark is replaced by a b-quark. It should be noted that there were

studies which concluded that large B-meson mixing requires a very heavy top-quark mass[31] within the framework of the Standard Model and that it had serious impact on the research program of the TRISTAN at KEK.[32],[33]

Since particle-anti-particle mixing leads to CP violation in K^0-meson decays, likewise, one would imagine that a B^0-meson mixing with its anti-particle may lead to CP violation in B^0-meson decays as noticed out by Sanda *et al.*[29] However, CP violation manifests itself in a quite different manner in the B-meson case. I.I. Bigi and A.I. Sanda[34] found that CP violation appears in the form of a difference in the time-dependent decay rate of a B^0-meson to the specific final state to which both B^0-mesons and $\bar{B}^0$-mesons can decay.

Although they came up with a proper formula of the CP violation, their conclusion was that the magnitude of the CP asymmetry would be small due to small B^0-$\bar{B}^0$ mixing (the top quark mass was thought to be much less than 100 GeV at that time) and it would be difficult to measure because of the presumably short life time of B-meson. I.I. Bigi and A.I. Sanda[34] revisited their study after the discovery of the long life time of B-meson in 1983 but their conclusion was again that "CP violation induced by the B^0-$\bar{B}^0$ mixing will be very hard to observe if the standard six-quark model is correct", although they noticed in the same paper that the mixing induced CP violation could be as large as 10%.

The discovery of large B^0-meson mixing has triggered to explore the possibility to find CP violation in B^0-meson decays[35] by generating B^0-mesons in various ways of particle collisions. According to the scenario of I.I. Bigi and A.I. Sanda,[34] one of the possible ways is to compare the time-dependent-decay-rate of B^0-meson decay to a certain CP eigen-states with that of anti-B^0-meson decay to the same final states.

The challenge is how to measure the time-dependent-decay-rate of the B^0-meson with a life time as short as $\sim$1.6 psec. This measurement can be made if the B^0-meson moves with reasonable momentum so that its passage can be traced from the point of generation to the point of decay. Such B^0-mesons can be produced by high energy electron-positron collision, proton-proton collision and proton-anti-proton collision; B^0-mesons were most intensively studied with electron-positron collision at Upsilon (4S), where B^0-mesons were produced almost at rest as mentioned above.

For the study of the time dependent decay rate of B-meson, an interesting approach[35] was proposed. If the Upsilon(4S) is produced with substantial momentum, the B-meson's momentum, P_{lab}, also becomes large and is approximately one half of $P_{Upsilon}$. Two B-mesons move in parallel along the direction of the motion of the Upsilon (4S) resonance.

$$P_{lab} = 1/2 \times P_{Upsilon}.$$

The advantage of this arrangement is that it makes it possible to study the decay time profile of both meson and anti-meson in a quite similar experimental environment. The other advantage of this arrangement is that once one of the produced B-mesons is identified as a B^0 (or a $\bar{B}^0$) at a certain time, the accompanying particle should be a $\bar{B}^0$ (a B^0) at this moment. Then, the accompanying particle can evolve in time to a B^0 (a $\bar{B}^0$) with given probability because of the particle-anti-particle mixing. The formula to calculate the probability of finding a particle or an anti-particle at a certain time was worked by Sanda *et al.*[29]

As is described later, this special scheme of B-meson creation can be realized by the asymmetric energy collision of an electron and a positron[35] in which an Upsilon(4S) resonance can be produced with some momentum and subsequently decays to B-mesons.

4. Asymmetric energy electron-positron collider for B-meson studies[35]

A schematic image of B-meson pair production by asymmetric energy collision is given in Fig. 2. In this figure, produced B-mesons are boosted in momentum by the difference of momentum between the electron and the positron, $\Delta p = p_{electron} - p_{positron}$, where $p_{electron}$ is the momentum of electron and $p_{positron}$ is the momentum of positron. Then each B-meson gets momentum which is equal to $\Delta p/2$, if one neglects the momentum of the B-meson in the rest frame of the Upsilon (4S). For the collision of an 8 GeV electron and a 3.5 GeV positron, $p_B = 2.25$ GeV. The B-meson traverses on average about $l = 200\,\mu$m before it decays.

There were proposals[36],[37] for constructing an asymmetric energy electron-positron collider at the Upsilon(4S) resonance at several places in the world: SLAC, Cornel University, DESY, PSI, BINP and KEK. The primary goal of the proposals was to observe CP violation in B-meson decays given the magnitude of CP violation expected from available experimental information and assumptions. Two
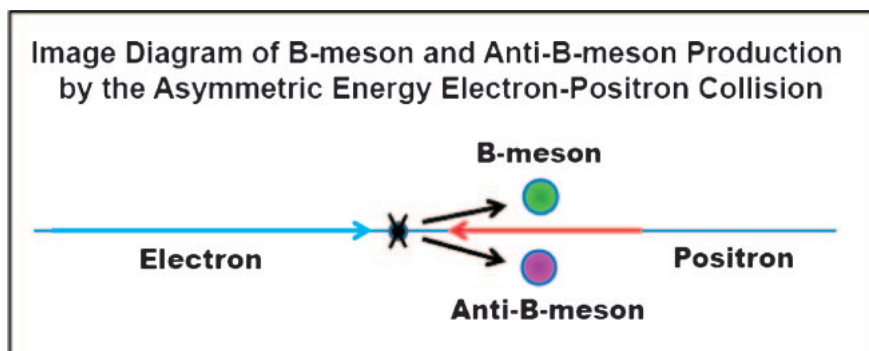
Fig. 2. An image of B-meson pair production at the Upsilon (4S) resonance by the asymmetric energy collision of the electron and positron.

B-factory projects were approved for construction by 1993, one at the KEK[38] and the other at the SLAC.[39]

At KEK, a taskforce[5] was formed to make a feasibility study for the construction of an asymmetric energy electron-positron collider and it was decided to be built in the existing TRISTAN tunnel, as is discussed in the following section.

5. The KEK B-factory project (KEKB Project)

While the TRISTAN accelerator was in operation, discussion on a B-physics project at KEK started in 1988 which was to build an asymmetric energy electron-positron collider on the KEK campus.[5,6] When the asymmetric energy collider project started, there was also a study group which intended to build a B-factory using the symmetric energy collision of electron and positron beams using the 6.5 GeV TRISTAN accumulation ring.[5,6,40] In 1989, The TRISTAN Program Advisory Committee recommended that the B-factory with the asymmetric energy electron-positron collision should be built as soon as possible as for the KEK's competitive program following the TRISTAN project.[5,6]

Case studies were made for several accelerator designs for possible construction sites on the KEK Tsukuba campus, focusing on the optimization of the experimental parameters, including the choice of the beam energies. The initial design of the KEK B-factory was to use the TRISTAN ring for the high energy electron synchrotron with a positron ring with much smaller circumference to be added to the existing TRISTAN electron ring.[41] It was a study by K. Hirata and E. Keil[42] which pointed out that unequal circumference of the synchrotrons in an asymmetric energy collider may increase the coherent beam-beam resonance, which could be a source of beam instability, and that such a configuration should be avoided. Since their study, discussions were limited to using the same circumference rings of the electron and positron beams.[37,43]

A preferred accelerator design discussed in the early stage of the project was to build a new accelerator in a new tunnel with a circumference of about 1300 m[43] like the one proposed at the SLAC, the PEP-II, while the existing TRISTAN accelerator should be converted to a new photon factory facility.[5] This is partly because of the fact that the 3 km long circumference of the TRISTAN ring would require a powerful LINAC to fill the positron ring with high beam current. The existing 2.5 GeV LINAC of KEK was considered to be far inferior to the competing project at SLAC which uses a 50 GeV LINAC for the beam injector and it could be potentially a serious drawback of the KEK B-factory in competing with the SLAC B-factory. The upgrade of the LINAC was on the top of agenda for the KEKB project.

While the long circumference of the KEKB B-factory storage ring requires a powerful injector, it provides redundancy and flexibility in the arrangement of accelerator components. It makes it possible to have sophisticated manipulation of the beams and it leads eventually to have higher luminosity, as was proven by the real KEKB accelerator.

The construction of the KEK B-factory was started in 1994. It has two synchrotrons, a 3.5 GeV positron storage ring and an 8 GeV electron storage ring, to be housed in the existing TRISTAN tunnel.[5,6,38] Figure 3 shows a schematic view of the KEKB accelerator complex. The luminosity goal[38] was set to be $1 \times 10^{34} \, \mathrm{cm}^{-2} \mathrm{sec}^{-1}$, about
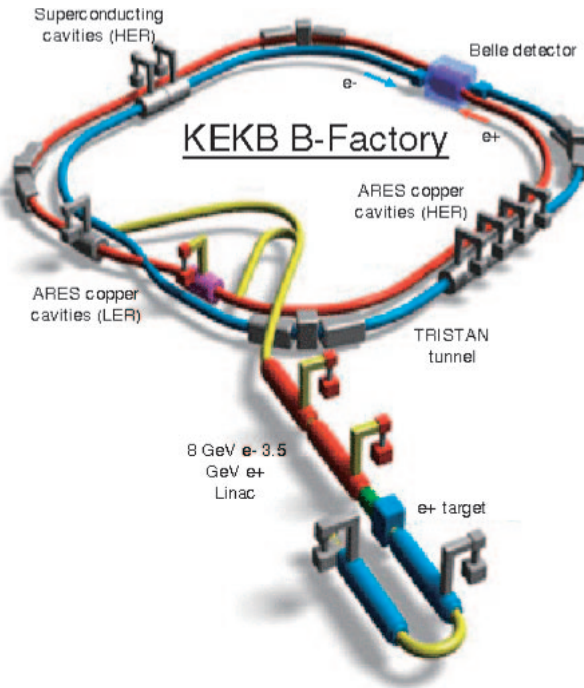
Fig. 3.   The Schematic view of the KEKB accelerator complex.

1,000 times higher than that of TRISTAN and the highest of the any colliding beam accelerator ever built in the world. The circumference of the synchrotron storage rings is 3,016 m.

In this design, the electron LINAC was upgraded so that both 8 GeV electron beam and 3.5 GeV positron beam can be generated and can be injected to the collider rings directly. The energy upgrade was made by the elongation of the accelerating LINAC section to have more acceleration units in the LINAC, and also by the adaption of the SLED scheme to double the RF acceleration voltage[44] per unit length.

Figure 4 shows the upgraded KEK LINAC, the newly added arced section of the LINAC and the RF pulse doubling network, the SLED.

Furthermore the "Top-Up" operation scheme for both beams improved dramatically the effective luminosity available for the experiment. The simultaneous injection of both electron and positron beams together improved further the effective luminosity. These operation scheme narrowed the gap of beam supply capability between the KEKB project and the SLAC B-factory project. It should be noted that the KEK LINAC has to also supply beams to the 2.5 GeV and 6.5 GeV photon factory synchrotrons in addition to the KEKB synchrotrons.

Along with the LINAC upgrade, there was a concern whether the RF cavities could provide sufficient RF power to operate the synchrotron at high beam current, especially in the positron ring. For this purpose, a new RF cavity was developed. It was the use of the ARES[45] cavities (See Fig. 5.) which enabled smooth and robust operation of the high current beams. The installation of this cavity was possible due to the large cross sectional space of the TRISTAN tunnel.

Another instrument to be mentioned is the extensive use of the wiggler magnets[46] as shown in Fig. 6, in order to shorten the damping time of the betatron oscillation of the positron beam. It made it possible to have a similar damping time for both electron and positron beams.

The parameters of the accelerator at the early stage of its operation are given in reference 47. The designed luminosity, $1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$, was achieved in May 2003. The key parameters of the accelerator to achieve this luminosity are the following: The electron and positron beam currents were 1.05 A and 1.38 A, respectively, with the number of beam bunches was 1284. Beams were squeezed down to 2.3 μm in the vertical direction and 110 μm in the horizontal direction at the beam collision point. The beam length was about 6 mm.

With this luminosity, about 10 B and $\bar{\mathrm{B}}$ meson pairs could be produced every second, or 100 million events for 10^7 sec, about 1/3 of a year, for a cross section of about 1 nb (nb $=10^{-33}\,\mathrm{cm}^2$) at the energy of the Upsilon(4S) resonance. One of the special feature of the KEKB design is the use of finite angle crossing, ± 11 mrad, at the beam collision point.[38] The finite angle crossing of the beams is favorable from the view points of 1) making the design of the beam separation at the beam collision point much easier, 2) lessening the parasitic interaction of the beams, and 3) reducing the beam induced backgrounds to the detector. There was a serious concern for this idea by the international review committee of the KEKB project. It was worried that the finite angle crossing of beams could become a potential source of the beam instability,[48] which in turn may limit the achievable luminosity. After in-depth discussion with the KEKB accelerator team and the review committee, it was agreed to go with this original idea. Later it was proven that the finite angle crossing of beams does not create instability of beams and KEKB recorded the world highest luminosity, 1.76×10^{34} cm^{-2} sec^{-1}.[48] It was further improved to $2.1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$ by incorporating the crab cavity.[49]

Fig. 4.   Pictures of the upgraded LINAC: The straight section (upper left), the arced section (upper right) and the RF pulse doubling network, the SLED (bottom).

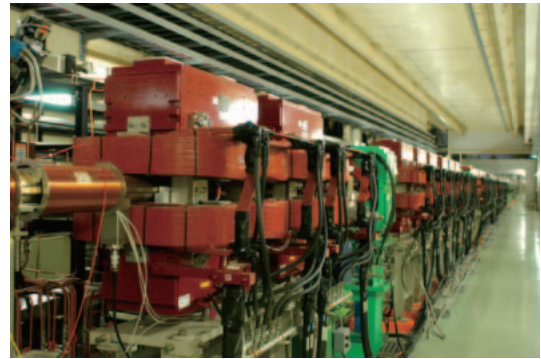Fig. 5.   ARES cavities in the KEKB tunnel.

Fig. 6.   A picture of the wigglers in the KEKB tunnel.

6. The Belle experiment

In the mean time, an experiment group was formed in 1993 by people from many Japanese as well as overseas institutions, and this experiment was named Belle.[50] The major goal of the experiment was to learn if CP symmetry is violated in the B-meson decays as was studied by Sanda *et al.*[29] The detector was designed[51] so that the CP violation could be observed with 3σ significance with an integrated luminosity of $10\,\mathrm{fb}^{-1}$, which corresponds

Belle Detector

SC solenoid
1.5T

Aerogel Cherenkov cnt.
n=1.015~1.030

CsI(Tl)
16X_0

3.5 GeV e^+

TOF conter

8 GeV e^-

Central Drift Chamber
small cell +He/C_2H_6

Si vtx. det.
3 lyr. DSSD

μ / K_L detection
14/15 lyr. RPC+Fe
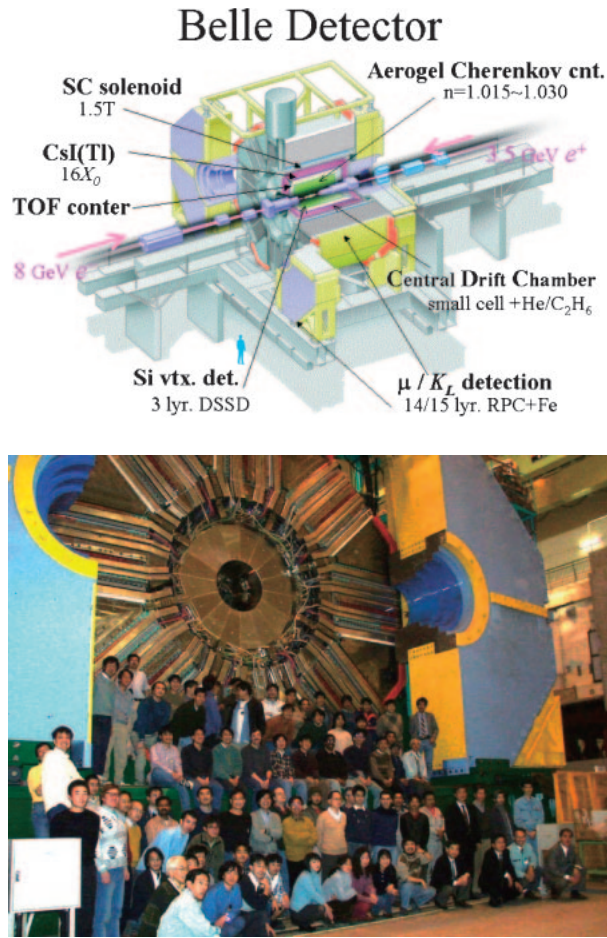
Fig. 7. A schematic view of the Belle detector (upper figure) and its picture (bottom figure).

Fig. 8. A picture of the Silicon Vertex Detector.

(CDC), an array of the aero-gel threshold Cherenkov counters (ACC),[52] time-of-flight counters (TOF), and a calorimeter made of array of CsI crystals (ECL) located inside a superconducting solenoid of 1.5 Tesla. An iron flux return located outside of the solenoid is instrumented to detect K_L mesons and to detect muons (KLM).[53] Figure 8 shows the SVD, Fig. 9 is the endplate of the CDC, and Fig. 10 is a tile of an Aero-gel radiator for the Cherenkov counter together with a schematic view of the counter assembly.

Produced particles are identified using the information from various components of the Belle detector. For example, electrons are identified by the precise measurement of their momentum and its good matching with the energy deposit in the calorimeter. Muons are identified by the fact that they penetrate all through detector components from the beam collision point down to the end of muon detector. Identification of pions and K-mesons is made by the combination of information of 1) energy loss in the CDC, 2) signals in the ACC and 3) information of the TOF.

The requirement imposed on the detector is that it enables 1) to identify B-mesons and anti-B-mesons separately and 2) to measure the difference of decay points of B-meson pair (Δz) with an accuracy better than 100 μm. They are minimum requirements of the detector necessary to measure the time distribution of B-meson decay points. The required performance of the Belle detector is described in the reference 52 in detail.

By the collision of a 3.5 GeV positron beam with an 8 GeV electron beam, the produced B-mesons have a momentum of about 2.25 GeV and a mean

to the detection of 10 million B-$\bar{\text{B}}$ events, or a year running (10^7 sec) with the average luminosity of 10^{33} cm^{-2} sec^{-1} assuming the magnitude of CP asymmetry, $\sin(2\phi_1)$, to be as large as 0.6. The definition of the CP asymmetry, $\sin(2\phi_1)$, is given later in section 9. The magnitude of CP asymmetry turned out to be quite large as expected, and CP violation was actually discovered in 2001, about two years from the start of the experiment.

A schematic view of the Belle detector is shown in Fig. 7. The upper figure is a schematic view of the detector and the bottom figure is a picture taken when the whole assembly was completed.

The Belle detector is a large-solid-angle magnetic spectrometer which consists of a vertex detector made of three layers of the double sided silicon strip detectors (SVD), a charged particle tracker made of 50 layers of multi-wire cylindrical drift chamber
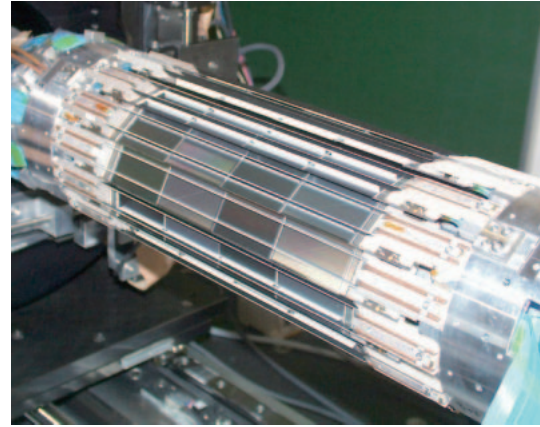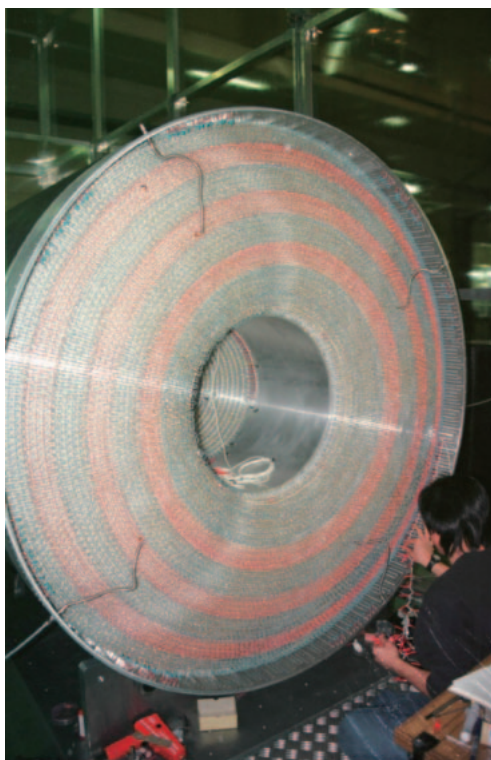
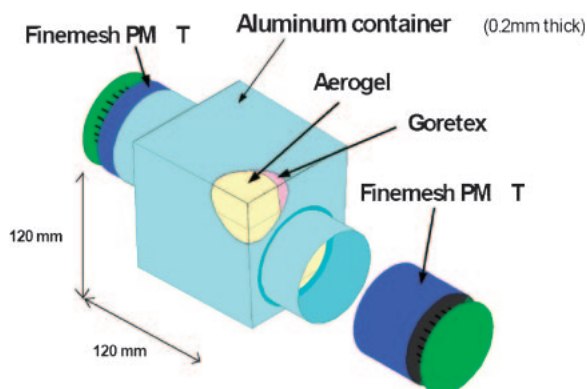Fig. 9.   Checking the endplate of the central drift chamber.

Fig. 10.   A picture of a tile of an Aero-gel radiator for the Cherenkov counter (Top figure) and a schematic view of the counter assembly (Bottom figure).

flight length of about 200 μm. Therefore, the precision of the decay position measurement of a B-meson, designed to be better than 50 μm, would be accurate enough to measure decay time distribution. The accurate measurement of the decay point owes to the Vertex Detector (SVD) made of three layers of double-sides silicon strip detectors located just outside of the beam pipe at the collision point of electron and positron beams.

7. Commissioning of the accelerator and experiment

The project was in hard competition with the similar project[39] at SLAC, which started construction about half a year earlier than KEKB. SLAC is known for the successful construction and operation of the electron-positron colliders such as SPEAR, PEP, and SLC and it has outstanding record of discoveries such as the J/Ψ[8] particle and the tau lepton,[17] the observation of constituent particles within a nucleon and the first measurement of the B-meson life time.[24]

The project encountered many difficulties, as is always the case with ambitious research projects. For the accelerator, the most serious problem was the unexpected instability of the positron beam induced by the interaction of positron bunches with the copious electrons, "electron clouds", that are generated at the wall of the beam pipe by the synchrotron radiation from the positron beam,[54] and which remain in the beam pipe. Because of the low momentum of photo-electrons, they could be suppressed easily by applying a weak magnetic field without affecting the motion of the beam bunches. Studies were made by attaching number of permanent magnets on the beam pipe covering most part of the drift space of the positron synchrotron as shown in the Fig. 11 (upper figure). After confirming the suppression of the instability by the magnetic field, the permanent magnets were replaced by the coils[55] which were wound around the vacuum pipe as shown in the Fig. 11 (lower figure). Although the beam instability was not cured completely, the performance of the collider was improved substantially by applying magnetic field.

As for the detector, the biggest challenge of the Belle experiment group was how to build a silicon

Fig. 11.   Pictures of the positron ring with permanent magnets placed around the beam pipe (Upper figure) and the coils wound around the beam pipe (Lower figure) to suppress the effects of electrons produced by synchrotron radiation from the positron beam.

Fig. 12.   A typical event observed by the Belle detector.

vertex detector (SVD)[56] with high performance. It consisted of many pieces of double-sided silicon strip detectors which can measure the two coordinates of the position of charged particle hitting at the detector. This detector is designed to measure the decay point of a B-meson with an accuracy of $50\,\mu m$. This accuracy is sufficient to measure the time-dependent decay rate of B-mesons produced by the electron-positron collision, because B-mesons traverse about $200\,\mu m$ on average before they decay after creation by the electron-positron collision. Since it is the most important task of the experiment to measure the decay point of B-mesons, it was a big concern of the experiment to have high performance of the SVD. The SVD is placed around the beam collision point just outside of the beam pipe and therefore could be exposed to the high level of radiation generated by the circulating beams. In fact the SVD used at the time of the beam commissioning
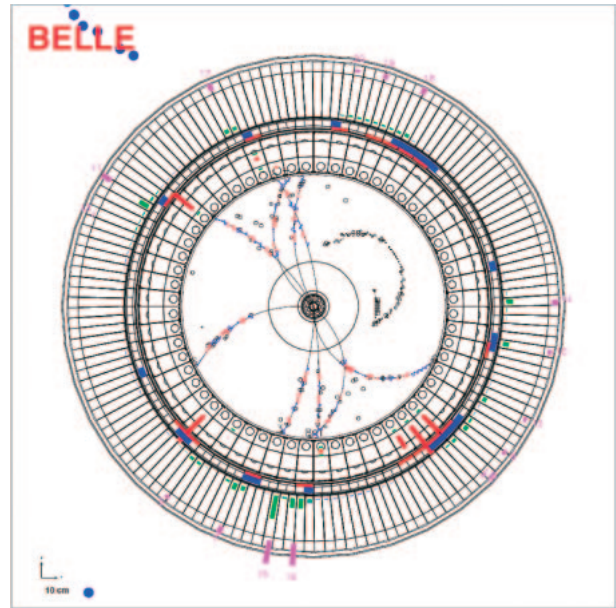
was destroyed soon after the beam delivery to the storage ring and it had to be rebuilt. Since the rebuilt SVD was much more radiation tolerant and the reinforcement of the radiation shield was made, the SVD functioned properly to measure tracks of charged particles and used for the measurement of the B-meson decay point successfully afterward. After tuning all detector components, the experiment was carried out smoothly without serious problems. Figure 12 shows a typical event observed by the Belle detector.

Since a huge number of particles are produced by the circulating beams which go through the detector, it is required for the detector to be equipped with an event trigger system to select properly events which are needed for the experiment. All components of the Belle detector registered their signals on their memory upon receiving a registration signal issued by the event trigger system[57] and signals were transferred to the data storage afterward. To issue this registration signal, it is required that some number of charged tracks goes through the CDC or some amount of energy is deposited on the ECL. Events containing B-meson pairs have to be selected from a huge number of stored events which include events of production of other quarks, muons and electrons, as well as background events which are generated by off-orbit beam particles hitting the materials around the beam pipe.

8. Analysis and results of the experiment

We describe the analysis method to show how the measurement of CP violation in B-mesons was made. First of all, we select events containing a pair of B-mesons. One of the B-mesons is reconstructed by knowing that it decays to a CP eigen-state, f_{CP}, such as J/Ψ Ks and D$\bar{D}$Ks. Then, we "tag" the flavor of another B-meson by knowing the fact that it decays to a flavor specific state, f_{TAG}, such as $X^+ l^-$v, where X can be any hadronic states and l^- is a negative lepton such as an electron or a negative muon.

Then, decay positions of the two B-mesons are reconstructed. The difference of decay times of the two B-mesons, $\Delta t = t_{TAG} - t_{CP}$, can be measured from the distance between the two decay positions, $\Delta z = z_{TAG} - z_{CP}$, as $\Delta t = \Delta z / c\beta\gamma$.

The time dependent CP asymmetry $A_{CP}(\Delta t)$ is given by the following equation:

$$A_{CP}(\Delta t) = \{\Gamma(\Delta t: \bar{B}^0 \to f_{CP})$$
$$- \Gamma(\Delta t: B^0 \to f_{CP})\}/\{\Gamma(\Delta t: \bar{B}^0 \to f_{CP})$$
$$+ \Gamma(\Delta t: B^0 \to f_{CP})\}.$$

Here $\Gamma(\Delta t: \bar{B}^0 \to f_{CP})$ and $\Gamma(\Delta t: B^0 \to f_{CP})$ are the decay rate of $\bar{B}^0$ and B^0 to the state f_{CP} at Δt.

The asymmetry is given as

$$A_{CP}(\Delta t) = \xi \sin(2\phi_1) \sin(\Delta m \Delta t).$$

In this equation, ξ is CP eigen-value ($+1$ or -1) of the f_{CP}, ϕ_1 is one of the three angles of the CKM unitary matrix,[26]

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

and ϕ_1 is defined as

$$\phi_1 = \pi - \arg(V_{tb}{}^* V_{td}/V_{cb}{}^* V_{cd}).$$

Here, V_{ab}s are the CKM unitary matrix elements representing the amount of quark mixing between the quark-a and quark-b, as given in reference 25.

Since B-meson and $\bar{B}$-meson mix each other, two mass-eigen states of B-meson can be defined with masses, m_H and m_L. Δm is the difference between the two mass eigen-states,

$$\Delta m = m_H - m_L$$

Δm is measured to be $0.507 \pm 0.005 \, \text{ps}^{-1}$.[26] $\sin(2\phi_1)$ is the magnitude of CP asymmetry, which we would like to measure by this experiment.

We describe the way to find events containing B-mesons among many background events for the case of a typical decay mode, $B^0 \to J/\Psi$ Ks. First we look for a J/Ψ particle by the detection of its decay products, an e^+ and e^- pair or a μ^+ and μ^- pair. The Ks can be also identified by the detection of a π^+ and π^- pair. They can be easily separated from the background processes by forming their invariant masses as shown in Fig. 13.

Then, we calculate the invariant mass formed from J/Ψ and Ks. As shown in Fig. 14, B-mesons are clearly identified. In this analysis, a constraint is imposed that the calculated energy of the B-meson equals one half of the beam energy, the sum of energies of the incoming electron and positron.

It should be noted that once one finds a B-meson in the final state and excludes the particles originating from this meson, the remaining particles in the final state should be those particles originating from the other B-meson. Then, if one finds a charged lepton or D-meson among them, $B^0 \to e$ X, μX and Dπ, we can tell if the mother B-meson is a particle or an anti-particle. This process is called "tagging" B-mesons. Two mesons remain in a coherent p-wave state until one of them decays. When one of the B-mesons decays to a state, f_{TAG}, at time, t_{TAG}, the accompanying meson is known to be an opposite b-flavored meson at t_{TAG}.

Decay time of the B-meson to the CP eigen-state such as J/Ψ Ks, t_{CP}, can be measured by knowing the decay point of J/Ψ. It is due to the fact of very short life time of J/Ψ and therefore, decay point of J/Ψ can be taken as decay point of B-meson.

Now, one can deduce the decay time difference between the two B-mesons,

$$\Delta t = t_{TAG} - t_{CP}.$$

Figure 15 shows an example of how the two decay points are reconstructed. In the figure, the point of B-meson decay including J/Ψ is known from the point of interception of muon tracks from J/Ψ, while the point of B-meson decay to the tag state, f_{TAG}, is measured by the point of interception of the tracks from the other B-mesons.

The performance of the KEKB accelerator improved at a dramatic rate. Figure 16 shows the history of accumulation of luminosity recorded by the Belle detector.

The accumulated luminosity by the Belle experiment increased rapidly and number of observed events also increased accordingly. Thanks to the huge data sample collected in a short time period, the Belle collaboration successfully measured CP viola-

Fig. 14.   Invariant mass distribution formed by the J/Ψ particle and Ks meson showing the peak corresponding to the B⁰ meson.
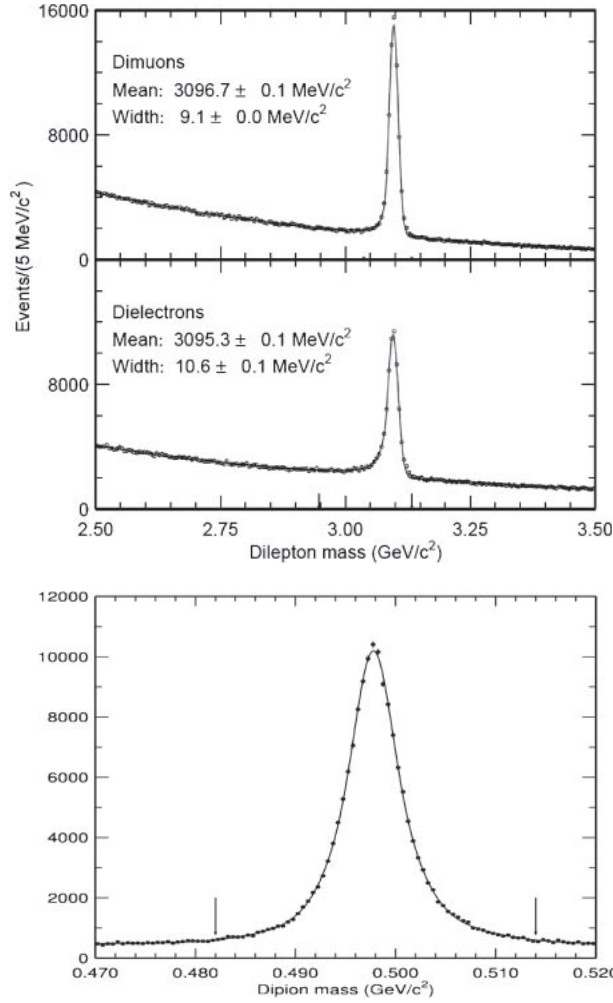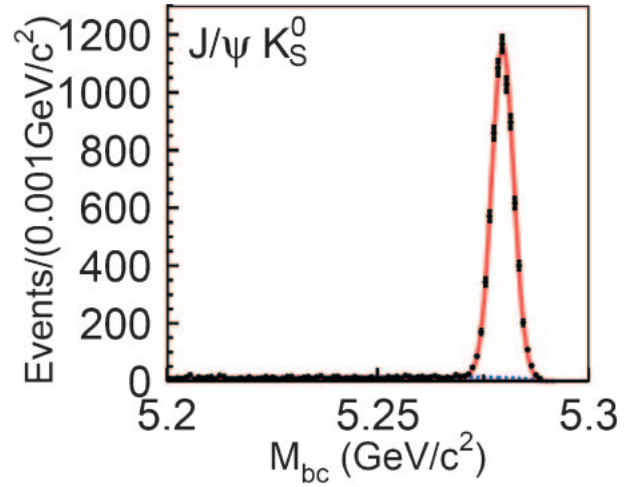

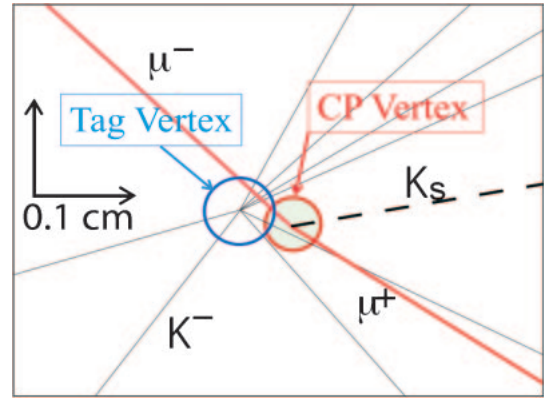Fig. 13.   Invariant mass distribution for lepton pairs showing the peak corresponding to the J/Ψ particle (upper two figures), and that for pion pairs showing the Ks meson (bottom figure).

Fig. 15.   Decay points of two B-mesons which are produced by the electron-positron annihilation.

tion in B-meson decays. The Belle collaboration published the result of CP violation measurement in B-meson decays first in March, 2001,[58] with the accumulated luminosity of $10.5\,\mathrm{fb}^{-1}$ after about one year from the start of data taking. Although the statistical significance is still limited, the result indicated CP violation in B-meson decays.

$$\sin 2\phi_1 = 0.58 + \{0.32 - 0.34 \ (\text{stat})\}$$
$$+ \{0.09 - 0.01 \ (\text{syst})\}.$$

By using more data sample, $29.1\,\mathrm{fb}^{-1}$, we came to the result showing the observation of CP violation in B-meson decay in August 2001[1] with more than 5σ significance.

$$\sin 2\phi_1 = 0.99 \pm 0.14 \ (\text{stat}) \pm 0.06 \ (\text{syst}).$$

It should be noted that many decay processes of B-meson other than those mentioned before are included to get the final result. They are:

$$\mathrm{J}/\Psi \ \mathrm{Ks}, \Psi(2\mathrm{s})\mathrm{Ks}, \chi_{c1}\mathrm{Ks}, \eta_c\mathrm{Ks} \ \text{and} \ \mathrm{J}/\Psi \ \mathrm{K_L},^{1),58}$$

here $\Psi(2\mathrm{s})$, χ_{c1} and η_c are bound states made of a c-quark and anti-c-quark with different quantum numbers.[26]

The most updated result of the CP violation parameter measured by the Belle experiment for a data sample corresponding to the accumulated luminosity of $711\,\mathrm{fb}^{-1}$ is given below,[59]

$$\sin 2\phi_1 = 0.668 \pm 0.023 \ (\text{stat}) \pm 0.013 \ (\text{syst}).$$

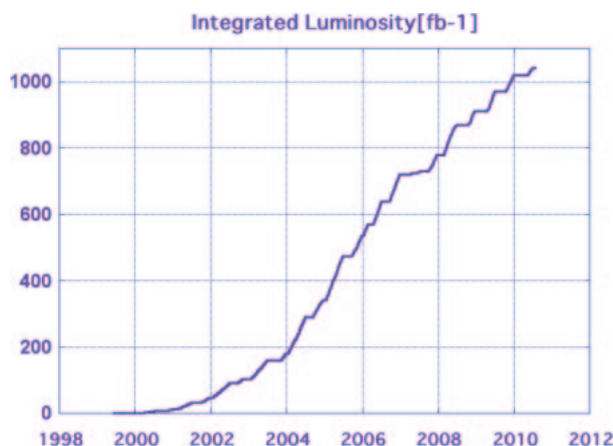Figure 17 shows the decay probability distributions for B-meson tagged events and B-meson tagged

Fig. 16. The history of accumulation of luminosity recorded by the Belle detector integrated luminosity exceeds the $1,000\,\text{fb}^{-1}$ at the end of the year 2009.

Fig. 17. Measured decay time distributions for B-meson tagged events (shown as $\bar{\text{B}}$-meson decay distribution in the figure) and $\bar{\text{B}}$-meson tagged (B-meson decay distribution in the figure) events. The difference in the time distribution shows the evidence for CP violation in B-meson decay. 772 million B-meson pair events were used to deduce this figure.

events obtained for the accumulated luminosity of $711\,\text{fb}^{-1}$. The difference between the two curves clearly shows the violation of CP symmetry. This is the evidence for CP violation first observed in the system other than Kaon decays and it is what I.I. Bigi and A.I. Sanda[34] noticed for the first time based on the Kobayashi-Maskawa theory. Therefore, it is the proof of the Kobayashi-Maskawa hypothesis that CP violation can be explained by the complex phase in the quark mixing.

9. Impact of the discovery of the CP violation in the B-meson decays

The Kobayashi-Maskawa theory of CP violation was proven by the discovery of CP violation in B-meson decays. It is a remarkable fact that the effort to explain a very small and minor effect of Kaon decay, CP violation, led to the prediction of the existence of six quarks and that it was successfully proven experimentally. This is a lesson that an observation and explanation of rare phenomena may open up an unexpected world and can be a key to understand unsolved puzzles of the world. These days, it is known that the Standard Model explains many properties of particles. It is also well known that there remain many puzzles which cannot be explained by the Standard Model. For instance, we do not know reasons for matter dominant universe, origin of particle masses, number of particle species, and so on.

It should be noted that thanks to extremely high luminosity of KEKB accelerator, Belle experiment was able to collect a huge data sample and it has
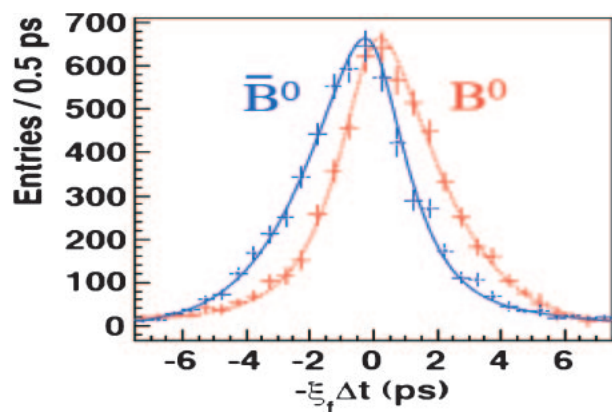
encountered phenomena which are difficult to be accounted for by the Standard Model. They are, for example, the evidence for D-$\bar{\text{D}}$ mixing[60] and the difference of the CP asymmetry for $\text{B}^0 \to \text{K}\pi$ and for $\text{B}^\pm \to \text{K}\pi$.[61] These phenomena could be a reflection of effects beyond the Standard Model. The Belle collaboration plans to make much more detailed studies of these effects and also to look for evidence for something unexpected or which may lead to the great discovery.

For detailed study of B-mesons, substantially more data are required and it has driven people to upgrade the accelerator to deliver an even higher luminosity than the present KEKB accelerator, which recorded the world highest luminosity of any particle colliders. It will be a big challenge. The KEKB accelerator and Belle experiment people came up with an ambitious upgrade plan. It is a proposal of the SuperKEKB accelerator[62] and the Belle-II detector.[63] It is intended to have a factor of 40 improvement of the luminosity with the adoption of nano-beam optics[62] and having more beam current. The Japanese government has approved their proposal. The upgrade of facilities has already started with the target date of completion to be in late 2015 or early 2016.

10. Acknowledgements

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Present author came to the similar idea in 1987 after the announcement of the large B-B mixing by the ARGUS collaboration and asked K. Oide to make a design of the asymmetric energy collider with the TRISTAN ring as the high energy electron synchrotron. K. Oide came up with a design with the finite angle collision in January, 1988.
It should be noted that the TRISTAN project was originally an ambitious one in which four types of colliders were planned to be built as a single accelerator complex: an electron-positron collider, an electron-proton collider, a proton-proton collider and a proton-anti-proton colliders. Among others, an in-depth study was made on the possibility of electron-proton collider. It was an asymmetric energy collider and study was made on the detection of particles produced in the forward angles as for the asymmetric energy KEKB collider. As for the reference on the original TRISTAN project, see following documents:
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Profile

Fumihiko Takasaki was born in 1943 and started his research career in 1966 on high energy physics, after graduating from the Faculty of science at the University of Tokyo. He studied properties of nucleon resonances with photon at the Institute of Nuclear Studies of the University of Tokyo and with kaon beam at KEK. He also engaged in the electron-positron collider experiment at TRISTAN, KEK and served as one of the spokespersons of the VENUS experiment. Later he proposed an asymmetric energy electron-positron collider to look for the CP violation in the B-meson decays at KEK, the B-Factory and served as one of the spokes persons of the Belle experiment. This experiment discovered the CP violation proving Kobayashi-Maskawa theory. Similar experiment at Stanford, U.S.A., also discovered the CP violation almost simultaneously. Present author and Katsunobu Oide, leader of the B-factory accelerator, were awarded with the Nishina Prize in 2001. Fumihiko Takasaki became a professor of Particle and Nuclear Physics Institute of KEK in 1986 and served as its director for three years from 2006 to 2009. He also served as a Trustee of KEK from 2006 to 2012.